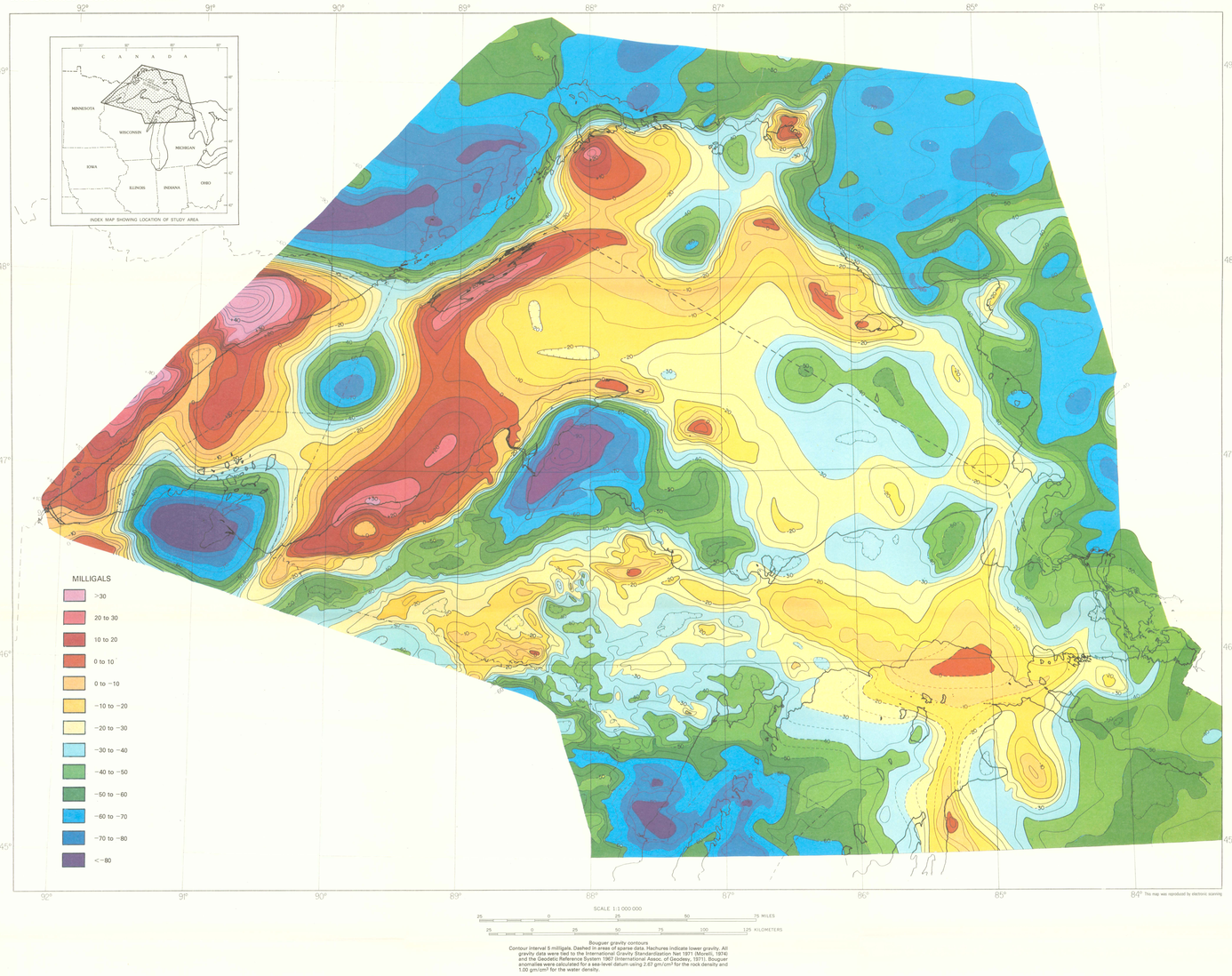

Bouguer gravity contours

Contour interval 5 milligals. Dashed in areas of extrapolation. Hachures indicate lower gravity. All gravity data were tied to the International Gravity Standardization Net 1971 (Morelli, 1974) and the Geodetic Reference System 1967 (International Assoc. of Geodesy, 1971). Bouguer anomalies were calculated for a sea-level datum using 2.67 gm/cm³ for the rock density and 1.00 gm/cm³ for the water density.

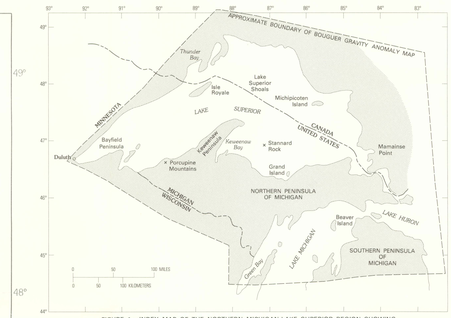

FIGURE 1.—INDEX MAP OF THE NORTHERN MICHIGAN-LAKE SUPERIOR REGION SHOWING LOCATION OF STUDY AREA AND GEOGRAPHIC NAMES USED IN THIS REPORT.

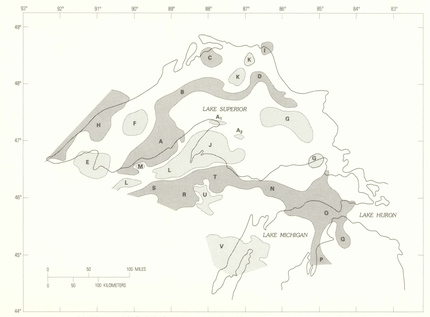

FIGURE 4.—MAP SHOWING LOCATION OF GRAVITY ANOMALIES REFERRED TO IN THE TEXT OF THIS REPORT. POSITIVE ANOMALIES ARE SHOWN BY DARK SHADING; NEGATIVE ANOMALIES ARE LIGHTLY SHADED

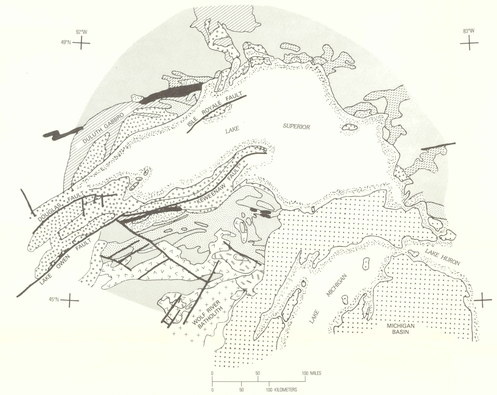

FIGURE 2.—GENERALIZED GEOLOGY OF THE STUDY AREA. AFTER DOUGLAS, (1972), CARD AND OTHERS (1972), AND SIMS, (1976).

EXPLANATION

PALEOZOIC ROCKS (<570 m.y.)

Sedimentary rocks

PROTEROZOIC ROCKS

PRECAMBRIAN Z AND Y (570–1600 m.y.)

Granite

Sedimentary rocks—includes Jacobsville Sandstone (not in Keweenawan Supergroup; in part Cambrian?) and Bayfield and Oronto Groups of table 3

Volcanic rocks—includes Portage Lake Volcanics of table 3

Mafic rocks—includes Duluth Complex discussed in text

Keweenawan Supergroup*

PRECAMBRIAN X (1.6–2.5 b.y.)

Granitic rocks

Iron-formation

Metasedimentary rocks

Metavolcanic rocks

ARCHEAN ROCKS

ARCHEAN (>2.5 b.y.)

Intrusive rocks: granitic, alkalic—includes Coldwell Complex discussed in text

Metavolcanic and metasedimentary rocks

Undifferentiated and metasedimentary rocks

*See Green (1977) for a detailed discussion of part of Keweenawan stratigraphy.

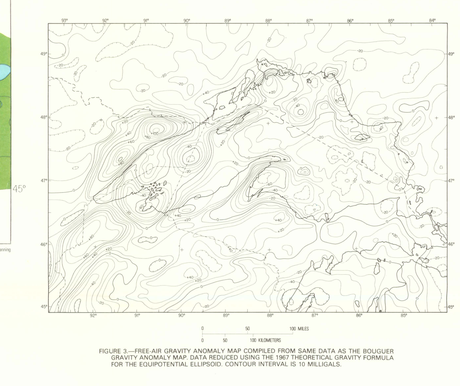

FIGURE 3.—FREE-AIR GRAVITY ANOMALY MAP COMPILED FROM SAME DATA AS THE BOUGUER GRAVITY ANOMALY MAP DATA REDUCED USING THE 1967 THEORETICAL GRAVITY FORMULA FOR THE EQUIPOTENTIAL ELLIPSOID. CONTOUR INTERVAL IS 10 MILLIGALS.

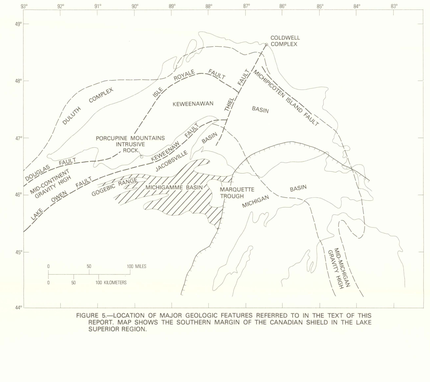

FIGURE 5.—LOCATION OF MAJOR GEOLOGIC FEATURES REFERRED TO IN THE TEXT OF THIS REPORT. MAP SHOWS THE SOUTHERN MARGIN OF THE CANADIAN SHIELD IN THE LAKE SUPERIOR REGION.

ACKNOWLEDGEMENTS

The compilation of gravity anomaly data for this map would not have been possible without the cooperation and assistance of many individuals and organizations. Special thanks are due to the several graduate students at Michigan State University and Michigan Technological University who collected and reduced the majority of the land data; Copper Range Exploration Company donated gravity data in the Keweenaw Peninsula area; C. D. Dankelson and P. J. Geraci of the U.S. Geological Survey made additional gravity observations and tied individual gravity surveys to the base network; and Dennis Bonnie, Thomas Stroka, and Alan Wilzinski of Western Illinois University assisted in the data compilation. Most data were reduced and initially compiled by the Defense Mapping Agency, Aerospace Center, St. Louis, Missouri from their gravity anomaly data files.

This compilation would not have been completed without the forsight and encouragement of William F. Cannon who recognized that such a map would be a valuable contribution to the geologic study of the northern peninsula of Michigan.

INTRODUCTION

The northern Michigan-Lake Superior region (fig. 1) has been the focus of continuing geological and geophysical investigations for more than one hundred years because of the presence of economic mineral deposits and because of the geologically interesting Keweenawan rift structure which forms the Lake Superior basin. The region is located on the North American craton along the southern margin of the Canadian Shield and is underlain by rocks that range in age from Phanerozoic within the Michigan basin to Archean in the western part of northern Michigan (fig. 2). The region has been affected by at least three major tectonic events: an orogeny that occurred about 2.5 b.y. ago (Archean); the Penokean orogeny that occurred approximately 1.9 b.y. ago (Precambrian X); and the Keweenawan rift event with associated igneous activity that occurred about 1.1 b.y. ago (Precambrian Y).

The complex geologic history of this part of North America has resulted in many geologic and structural features that can be detected and defined with geophysical data. Thus, the accompanying Bouguer gravity anomaly map, which is a compilation of available gravity data as of 1977, should aid in geologic and tectonic studies of the area. It covers the northern peninsula of Michigan, all of Lake Superior, parts of Lake Michigan and Huron, and the northern part of the southern peninsula of Michigan.

The purpose of this report is to explain the sources of data used in construction of the map and to briefly discuss the geologic and tectonic significance of the major gravity anomalies on the gravity anomaly map.

Before discussing the sources of gravity data and the geologic significance of the map, it is important to point out some limitations of the map. The gravity data used on this map, as shown in table 1, come from a variety of surveys which were conducted for different purposes, so that the quality of the data is highly variable. Also, especially on land, station spacing is highly irregular and, because of the inaccessibility to some areas, there are large gaps in station coverage. Station locations for most of the gravity data in the Lake Superior region, that is, Duluth Complex, Keweenawan, and Archean, are shown on the Bouguer gravity anomaly map (fig. 4). Locations of stations used in Rasmer and others (1977) for land areas and Wold and Berkson (1977) for Lake Superior.

As a result of the variable quality of the data, irregularities in station spacing, gaps in station coverage, and the small scale of the map, it is apparent that there are limitations in the amplitude and horizontal dimension of gravity anomalies that can be detected on this map. Most of the data sets from which the map was compiled are accurate to ±0.3 milligals or better as shown in table 2. This 0.6 milligal range places an ultimate lower limit on the amplitude of anomalies that might be significant and, in a practical sense, it is unlikely that an anomaly of less than 5 milligals (the contour interval used in the original compilation) would be significant at the 1:1,000,000 scale. The smallest station spacing used in construction of the gravity map is approximately 1.5 km (0.8 mi), but there are many areas where variations in the gravity field caused by geologic features with the smallest horizontal dimension being equal to or greater than twice the station spacing, 2 miles (3.2 km). In areas where station spacing is greater, such as over the lakes, the map will reliably detect only those features that cause gravity anomalies that are greater than 2 miles (3.2 km) in horizontal dimension. Therefore, individual intrusions and faults within the basins and minor igneous and structural features will not be delineated on the Bouguer gravity anomaly map.

A free-air gravity anomaly map has also been prepared and presented in figure 3. This map, which is a measure of the mass variations in the subsurface earth, is useful for specialized geologic and geodetic studies and is presented here for reference purposes only. It was compiled from the same data sets as the Bouguer gravity anomaly map.

SOURCE AND COMPILATION OF DATA

The spectrally colored 1:1,000,000-scale Bouguer gravity anomaly map was prepared from the 1:500,000-scale compilation (Rasmer and others, 1977). It conforms in scale to the adjacent Bouguer gravity anomaly maps of Minnesota (Craddock and others, 1969) and to the total magnetic intensity anomaly map of Michigan (Zietz and others, 1974). The 1:500,000-scale map was compiled from approximately 5000 gravity stations which were selected at a one-minute station spacing interval from a total of approximately 15,600 gravity stations. The sources of the 10,600 gravity stations are listed in table 1.

The gravity data were selected at one-minute intervals because of the high degree of variability in station spacing between individual gravity surveys and because of the close station spacing primarily in the western part of the northern peninsula of Michigan. Much of the land data was obtained along roads at station intervals ranging from 100 feet (30 m) to several miles. Also, because of inaccessibility to some areas, there are large gaps in gravity coverage, as much as 10 miles (16 km) between data points.

The selection of gravity stations at one-minute intervals was done by machine using a computer algorithm of the Defense Mapping Agency. The selection was done according to the latitude and longitude coordinates of each station so that no two stations are closer than one minute to each other. In this area, a one-minute quadrilateral is roughly 0.79 mi (1.3 km) east-west by 1.17 (1.88) mi (km) north-south. Gravity stations are not regularly spaced within a one-minute quadrilateral grid network; rather, they may be located anywhere within a one-minute quadrilateral depending upon the first station which was selected on the whole map, which in this case is the station with the lowest latitude and lowest longitude coordinate, i.e. the most southeasterly station on the map. In the western part of northern Michigan, where station spacing is denser, many stations were deleted in the selection, however, most of the map, station spacing is greater than one minute and no stations were deleted, nor were any added to the map by interpolation between observed stations. In the original compilation of the 5000 selected stations were posted to the nearest milligal and contoured by hand at a 5-milligal contour interval. A machine-contoured map was used as a guide.

REDUCTION OF DATA

All observed gravity values were tied to the Potsdam International Gravimetric Net and were recalculated to conform to the 1971 Unified International Gravimetric Net (Morelli, 1974).

Data were reduced to sea level using the 1967 theoretical gravity formula for the equipotential ellipsoid (Int. Assoc. of Geodesy, 1971). For land data, a Bouguer slab correction, the free-air and Bouguer anomalies were computed using the following formulas where all depths are given in meters:

Free-air anomaly = observed gravity + 0.3086 (lake elevation—water depth) + 0.0419(2.67 (water depth) − theoretical gravity)

Bouguer anomaly = observed gravity + 0.1968 (lake elevation—water depth) + 0.04191 (water depth)—theoretical gravity

For lake-based data rend with a lake-surface gravimeter, the data were reduced using the following formulas:

a) Lake surface above sea level, lake bottom below sea level:

Free-air anomaly = observed gravity + 0.3086 (elevation) —theoretical gravity,

Bouguer anomaly = observed gravity + 0.2667 (elevation) − 0.0699 (elevation—water depth)—theoretical gravity

b) Lake surface above sea level, lake bottom above sea level:

Free-air anomaly = observed gravity − 0.3086 (elevation) —theoretical gravity,

Bouguer anomaly = observed gravity + 0.3086 (elevation) − 0.04191 (water depth) − 0.1119 (elevation—water depth) —theoretical gravity

The land-based data were reduced using

Free-air anomaly = observed gravity + 0.3086 —theoretical gravity,

Bouguer anomaly = observed gravity + 0.1968 (elevation) —theoretical gravity.

The correction term for the water layer assumes that lake water has a density of 1.00 gm/cc and the Bouguer correction assumes an average rock density of 2.67 gm/cc.

ESTIMATE OF ERROR

There are four possible sources of error involved in the reduction of the data: elevation, latitude, rock density, and terrain correction. Accuracy estimates, in part based upon these sources of error, are given in table 2. These accuracy estimates are based on an accuracy code compiled by Robbins and others (1972), of the U.S. Geological Survey for land-based data in California. They represent our best judgement of how the majority of data for each of the several gravity surveys were obtained. From table 2 some general conclusions can be drawn about the overall accuracy of the map in terms of the possible sources of error.

Error due to incorrect elevation.—Table 2 indicates that most elevations for land-based data were determined from either stations located at points on U.S.Geological Survey topographic maps that have elevations indicated in black numbers (spot elevations) or at bench marks. The spot elevations are considered accurate to ±1.2 meters causing a possible ±0.2 milligal error in gravity. Elevation error estimates for lake-based data are considered to be no greater than this when lake-bottom gravimeters were used. The defense Mapping Agency survey employed a shipboard gravimeter and the inherent inaccuracies can be seen in the large estimated error of the data, ±4 milligals.

The gravity data were selected at one-minute intervals because of the high degree of variability in station spacing between individual gravity surveys and because of the close station spacing primarily in the western part of the northern peninsula of Michigan. Much of the land data was obtained along roads at station intervals ranging from 100 feet (30 m) to several miles. Also, because of inaccessibility to some areas, there are large gaps in gravity coverage, as much as 10 miles (16 km) between data points.

The selection of gravity stations at one-minute intervals was done by machine using a computer algorithm of the Defense Mapping Agency. The selection was done according to the latitude and longitude coordinates of each station so that no two stations are closer than one minute to each other. In this area, a one-minute quadrilateral is roughly 0.79 mi (1.3 km) east-west by 1.17 (1.88) mi (km) north-south. Gravity stations are not regularly spaced within a one-minute quadrilateral grid network; rather, they may be located anywhere within a one-minute quadrilateral

The maximum error in density anticipated in the survey area is approximately ±0.3 gm/cc which will produce a maximum error of approximately ±4 milligals at the surface elevation of this survey. This error can be eliminated in a quantitative gravity interpretation provided that the correct rock density is used in the reduction of the gravity data.

Errors due to lack of terrain correction.—With the exception of the Porcupine Mountain area, no terrain corrections were applied to the gravity data because observations were made in relatively flat terrain. A detailed gravity study by Klasner and others (1977) near the Huron Mountain area (not included on the gravity map because the whole survey falls within a two-mile radius) indicates that terrain corrections, even in this area of relatively high relief, are on the order of 0.2 milligal.

Total possible error.—According to table 2, the total maximum error for land-based data, excluding lack of terrain corrections and error in assumed rock density, is ±0.3 milligal. It is unlikely that all error factors will have the same sign so that, generally, total error will be less than this value.

GEOLOGICAL IMPLICATIONS OF THE GRAVITY ANOMALY MAP

General Comments

The Bouguer gravity anomaly map reflects variations in density caused by lithologic changes and structural effects which may occur from the surface to great depth. Interpretation to verify the source of gravity anomalies is difficult because of the complex geology in the southern peninsula of Michigan, which originate from intrabasement lithologic and structural variations, commonly have amplitudes of 10 milligals or more in contrast to anomalies less than 5 milligals which are related to basement topography, sedimentary structure, and bedrock topography. Gravity anomalies which originate from variations in the composition of the upper mantle and deeper crust, as well as from changes in the thickness of the crust, may reach amplitudes considerably in excess of 10 milligals, but the width of these anomalies are generally measured in hundreds of kilometers or more.

The potential sources of gravity anomalies in the Lake Superior region may be ascertained by comparing the densities, shown in table 3, of the major lithologic units in the Lake Superior region (fig. 2). It is apparent that accumulations of the relatively low-density sedimentary rocks of the Jacobsville Sandstone and Bayfield Group will result in relatively negative gravity anomalies where they are adjacent to higher-density metabasalt Keweenawan volcanic rocks. The older sedimentary rocks of the Oronto Group (Freda Sandstone) have a relatively higher density as compared to the Jacobsville Sandstone and Bayfield Group and will not contribute as significantly to the negative anomalies. The middle Keweenawan volcanic rocks and their intrusive equivalents are the highest density rocks that are widely distributed in the Lake Superior region. They produce anomalies of relatively large amplitude, especially where they have great depth extent due to either original deposition or structural deformation. It is also apparent from table 3 that the Precambrian X metasedimentary rocks have densities that are lower than most other rocks in the region, that is, Archean gneisses. For example, Kaiser and Cannon (1974) estimated that Precambrian X metasedimentary and metavolcanic rocks can average 0.22 gm/cc more in density than Archean basement rocks. Analyses of gravity data in the western Marquette Range area (Klasner and Cannon, 1974, and Cannon and Klasner, 1976) show that Precambrian X troughs within Archean rocks create positive gravity anomalies with amplitudes ranging from about 4 to 20 milligals.

Other gravity anomalies may be attributed to geologic features in which differences in rock density cannot be directly observed. For example, topographic irregularities at the basement or offset of alongate anomalies or gravity gradients might mark the position of a major subsurface fault or possibly a pinchout of a stratigraphic unit or intrusive body. Also, regional metamorphic isograds generally have associated gravity minima which are probably caused by subjacent, possibly felsic, intrusive bodies which have densities lower than the enclosing country rock.

These potential sources of gravity anomalies are useful in a semiquantitative sense, but their complexity can be in excess of unknown geology may lead to errors. They are most correctly used in extrapolating known geology on the basis of geophysical anomalies. Gravity anomalies seldom provide the complete subsurface picture and results are ambiguous. Where geologic data are unavailable to constrain the interpretation, other geophysical data, particularly magnetic data and near-surface and crustal seismic reflection and refraction data, are extremely useful in the correct interpretation of gravity anomalies.

Discussion of gravity anomalies over Lake Superior

To aid in the discussion of the geologic significance of individual gravity anomalies, positive and negative anomalies have been shaded and identified in figure 4. Also, figure 5 has been compiled to show the location of major geologic features discussed in this report. On figure 4, positive anomalies A, B, C, and D occur over mafic volcanic rocks of the Lake Superior syncline. Anomaly A occurs over an area in the lake where projection of the onshore geology suggests that the volcanic rocks thicken up to 10 km (Wihte, 1966). A_1 and A_2 mark the probable extension of Keweenawan volcanic rocks into Lake Superior from the Keweenawan Peninsula. Anomaly C occurs in an area where Halls and West (1971) measured up to 2 km of sedimentary rocks overlying a volcanic sequence. Weber and Goodacre (1966), from a 1964 underwater gravity survey, interpreted the same anomaly as being the result of a 10 km-thick sequence of middle Keweenawan lavas. Anomaly B occurs over Isle Royale where middle Keweenawan lava flows outcrop on the north limb of the Lake Superior syncline. Anomaly D occurs just east of Superior shoals, an area in the lake in which Parker (1964) dredged samples of middle Keweenawan volcanic rocks. This observation plus the apparent connection of this anomaly with anomalies A, B, and C suggests that the positive anomaly could be caused by mafic volcanic rocks. The relatively positive gravity high connecting anomalies B and D extends to the southeast over Michipicoten Island where middle Keweenawan mafic lava flows also crop out.

Anomaly E is a strong negative anomaly over the Bayfield Peninsula. White (1966a) attributes this anomaly to the intersection of a thick northward-trending trough of upper Keweenawan sedimentary rocks with a northward-trending ridge in the pre-Keweenawan rock. White (1972) suggests that above the gravity low connecting E and F, middle Keweenawan lavas are thin or absent thereby causing a negative Bouguer gravity anomaly. Anomaly G in eastern Lake Superior may be interpreted in a similar manner, that is a pre-Keweenawan ridge with thin or absent mafic volcanic rocks and an overlying sedimentary basin. However, Halls and West (1971) found that the cover of sedimentary rocks is thinner over anomaly G than it is over anomaly E. It is interesting to note that a magnetic high (Hinze and others, 1966) occurs over the center part of anomaly G. The gravity low may be caused by relatively thin mafic volcanic rocks above the pre-Keweenawan ridge and in part by the thin overlying sedimentary basin. The magnetic anomaly is caused by the near surface volcanic rocks.

Anomaly F is a large circular negative anomaly which has been interpreted by Anoskopo (1971) to be a 5 km-thick sequence of upper Keweenawan sedimentary rocks, but this differs from White's interpretation mentioned above.

Anomalies H and I occur over large Keweenawan intrusive complexes: the Duluth and the Coldwell Complexes, respectively. Anomaly H, however, actually peaks about 16 km northwest of Lake Superior. White (1966a) believes that the anomaly decreases in amplitude toward the lake because the gabbroic Duluth Complex thins to the southeast and pinches out entirely near the lake shore.

Anomaly J is a pronounced gravity low over sedimentary rocks (Jacobsville Sandstone) on the southeast flank of the Keweenaw fault. Bacon (1964) estimated from seismic data a 3 km displacement on the Keweenaw fault; downthrown to the southeast in the vicinity of anomaly J. It is apparent from the magnitude of the anomaly that if the volcanics are present they must be thin and pinch out to the south as suggested by Halls and West (1971).

Anomaly K is a gravity minimum just north of Superior Shoals. This anomaly along with the −40 milligal feature to the northeast lie along a pre-volcanic ridge proposed by Halls (1970) on the basis of gravity, magnetic, and geological data.

On land, steep gravity gradients occur along known faults shown in figure 5, primarily where volcanic rocks are in juxtaposition with sedimentary rocks. These faults can be projected beneath the lake on the basis of gravity data, but in the lake they are buried under the upper Keweenawan and Paleozoic sedimentary rocks and therefore the gravity gradients are less than in the land areas. The connection of the Douglas fault with the Isle Royale fault, which roughly follows the 0-milligal contour, is an example of such a projection. This interpretation was first made by Wold and Ostenso (1966) from gravity and magnetic evidence and is supported by White (1966b). Halls (1970), using additional magnetic data, also supports this interpretation.

The Isle Royale fault, which occurs along the north shore of Isle Royale, is expressed in the gravity data as a steep gradient (down to the northwest. It is traced eastward to Superior Shoals by Wold and Ostenso (1966) and Hinze and others (1966) from magnetic data. Halls and West (1971), from seismic studies, show that the north side of the fault is also relatively downthrown to the lake. The fault follows the 0-milligal contour (fig. 4) to about 87°40′W, 48°15′N and it appears to extend to the southeast to near the south edge of anomaly K where it terminates against a north-trending fault in the vicinity of Superior Shoals.

A major fault that crosses Lake Superior was interpreted by Hinze and others (1966) from magnetic data. The fault, which trends north-south, is expressed in the gravity data as a steep east-west trending magnetic anomaly along the fault trace and by a change in the anomaly pattern on either side of the fault. On figure 4, it occurs just west of anomaly L continuous southward along the high gravity gradient between anomalies D and E, and is apparently masked by thicker sediments in the center of the syncline between Keweenawan Peninsula and Superior Shoals. Seismic studies by Halls and West (1971) on the lake show no evidence of the fault at the surface but they interpret the Thiel fault (fig. 5) in honor of our deceased geophysical colleague, Edward C. Thiel who performed some of the pioneering geophysical studies in the Lake Superior region (Thiel, 1956).

A probable fault (fig. 5), parallel to the north shore of Michipicoten Island, was first suggested by Hinze and others (1966) from magnetic data. Weber and Goodacre (1966) and Halls and West (1971), from seismic reflection studies, confirmed the fault (Berkson, 1969). Halls and West (1971), from seismic reflection studies, also, confirmed the Michipicoten Island fault extends to the southeast in about 1 km. Bouguer gravity data, which are available only on Michipicoten Island, indicate the fault extends to the northwest as shown in figure 5, however the gravity data and seismic refraction data (Halls and West 1971) do not show any clear evidence for this fault extending to the northwest where it may be masked by overlying sediments.

The Keweenaw fault is extended to the southeast to near Grand Island in northern Michigan on the basis of magnetic data (Hinze and others, 1966). Gravity data support this extension at least to Stannard Rock and suggest that it continues to the south. The structural relationship between the Thiel fault and the Keweenaw fault just east of the tip of the Keweenaw Peninsula is not known at this time and warrants further study.

Discussion of gravity anomalies in northern Michigan area

The remaining anomalies on the gravity map can be divided into three groups according to the association with observed geologic features. Anomalies L, M, N, O, P, and Q (fig. 4) appear to be associated with structural or igneous features of the Keweenawan basin; anomalies R, S, and T are associated with Precambrian X basins; and anomalies U and V overlie Archean terrane.

Anomalies associated with the Keweenawan basin.—Gravity anomalies associated with the Keweenaw fault and the Keweenaw Bay region are discussed in the previous section. Anomaly L occurs over a part of Lake Superior. It is of note, however, that the gravity gradient associated with the Keweenaw fault extends into northern Wisconsin. Here the fault is known as the East Lake Owen fault (fig. 2). Also, the 90-milligal anomaly over Keweenaw Bay continues to the south (labeled L on fig. 4) into Michigan. It narrows and then widens near the Michigan-Wisconsin boundary. That part of the anomaly northeast of the narrow zone is associated with the Precambrian Z basin that extends southeast from the Keweenaw Bay region. That part southwest of the narrow zone overlies granitic rocks (see figs. 2 and 4) that are less dense than the Keweenawan basalts to the north and the rocks of the Precambrian Y sedimentary rocks to the south.

Anomaly M, just south of the Porcupine Mountains, is a small (5 miles (8 km)) oval anomaly that coincides with a prominent gravity gradient. Anomalies N, O, P, and Q have based by Oray and others (1973). They conclude that anomalies N and O are caused by accumulations of relatively thick Keweenawan basalt beneath the Phanerozoic strata of the Michigan basin. Although the Keweenawan basin narrows abruptly at this point, anomalies P and Q suggest that it continues as the mid-Michigan gravity high (Hinze, 1963) into the southern peninsula. Gravity models of anomalies P and Q show that they are caused by block faulting of Keweenawan basaltic rocks.

Anomalies associated with Precambrian X basins.—Anomalies R, S, and T are all associated with Precambrian X basins and troughs: S with the Gogebic Iron Range, R with the Michigamme basin, and T with the Marquette trough. Because of the abundant iron formations and other iron-rich rocks within these basins, the Precambrian X rocks are generally denser than the adjacent Archean rocks. Thus, the basins have associated positive gravity anomalies. However, gravity models of some of the troughs (Klasner and Cannon, 1974) indicate that the troughs are not large enough to account for the width and amplitude of associated gravity anomalies. A long wave length anomaly, approximately 50 miles (80 km) wide and ~40 milligals amplitude, with superimposed higher-frequency anomalies due to Precambrian X troughs, extends in an arc from near the Wisconsin-Michigan border at least to the intersection with the Keweenawan gravity feature in the eastern part of the northern peninsula of Michigan. It may be caused by density variations within the upper 10 miles (16 km) of the crust (Klasner and Bonnie, 1977).

Anomalies associated with Archean rocks.—Anomalies U and V are negative gravity anomalies which overlie Archean terrane. Anomaly U is also associated with the Republic node of regional metamorphism (James, 1955). James suggested that the concentric zones of regional metamorphism are caused by a subjacent plume buried about one mile (1.6 km) beneath the present surface. This would readily account for the negative anomaly over the metamorphic axes of the plume if the plume is composed of rock that is less dense than the country rocks. Anomaly U indicates that the Bouguer anomaly is in general, highly negative over the Archean terrane. It becomes more negative in Wisconsin and the gravity map of Wisconsin (Ervin and Hammer, 1974) shows that the Bouguer anomaly attains an amplitude of approximately −80 milligals in central Wisconsin.

TABLE 1. Sources of gravity data

Author	Approximate number of stations*	Date of survey	Area of study
Bacon (1957; 1964; 1970)*	6000	1951–52	Mostly the western portion of the northern peninsula of Michigan and the eastern part of northern Michigan.
Copper Range Exploration Company	500	1970	Southwestern portion of Keweenaw Peninsula, Michigan.
Defense Mapping Agency[2]	250	late 1960's	Northern portion of Lakes Michigan and Huron.
Hinze (1963)	180	1963	Northern portion of southern peninsula, Michigan.
Klasner and Cannon (1974); Cannon and Klasner (1976)	1040	1971–75	Northern peninsula, Michigan.
Miller (1966)	300	1962	Porcupine Mountain area, Michigan.
O'Hara (1972)	120	1970	Green Bay, Wisconsin.
Oray, Hinze, and O'Hara (1973)	1000	1971	Eastern portion of northern peninsula, Michigan.
Weidl and Berkson (1977)	1330	1965–67	Lake Superior.
Berkson (1969)	140	1967	Michipicoten Island area, Lake Superior.
Defense Mapping Agency			Portions of Minnesota and Wisconsin. The original sources of data are discussed in Craddock, and others (1969) and Ervin and Hammer (1974).
Geotech (1974)[3]			Portions of Canada adjacent to Lake Superior.

*Not all of the stations were used to prepare the Bouguer gravity anomaly map. Stations were selected so that no two stations are closer than one minute of latitude or longitude.

[1] The dates in parenthesis refer to original publications which discuss the gravity data listed in the table (see references cited).

[2] Private report, Copper Range Exploration Company, White Pine, MI 49971.

[3] Unpublished data from the Defense Mapping Agency, Gravity Division, St. Louis, MO 63118.

[4] Canadian data was purchased from Department of Energy, Mines and Resources, Canada.

TABLE 2. Accuracy of Data*

Author	Type of horizontal control	Type of elevation control	Terrain correction	Accuracy
L. O. Bacon	Spot locations on 1:62,500-scale maps	Black elevations on 20 ft contour interval[1]. Lines: Some bench mark and barometric altimeter control	None	±0.3 milligal
Copper Range Exploration Company	Chained from spot locations on 1:62,000-scale maps	Surveyed and tied to bench marks	None unnecessary	±0.1 milligal
Defense Mapping Agency	Spot locations on 1:1,000,000-scale maps determined by electronic tri-lateration	Lake-surface elevation and bathometer control for lake depths. Shipboard and bottom gravimeters	None	±4 milligals based on standard deviation of data
W. J. Hinze	Spot locations on 1:250,000-scale maps	Black elevations on 20 ft C. I. map. Some bench mark and barometric altimeter control	None	±0.3 milligal
J. S. Klasner and W. F. Cannon	Spot locations on 1:62,500-scale maps	Black elevations on 20 ft C. I. map. Some bench mark, barometric control, and contour interpolation on 20 ft C. I. maps	None	±0.3 milligal
N. W. O'Hara	Spot locations determined by radar fix and electronic tri-lateration tied to 1:1,000,000-scale map	Lake-surface elevation and bathymeter control for lake depths. Bottom gravimeter	None	±0.3 milligal author's estimate
Erdogan Oray and W. J. Hinze	Spot locations on 1:62,500-scale maps	Black elevations on 20 ft C. I. map. Some bench mark and barometric altimeter control	None	±0.3 milligal
W. R. Miller and W. J. Hinze	Spot locations on 1:62,500-scale maps	Lake-surface elevation and bathymeter control. Bottom gravimeter transducer in gravity meter for lake depths. Bottom gravimeter	Where necessary	±0.3 milligal author's estimate
R. J. Weidl and J. M. Berkson	Spot locations on 1:120,000-scale maps and referred to U.S.C. & G.S. triangulation stations by electronic navigation	Lake-surface elevation and pressure transducer in gravimeter for lake depths. Bottom gravimeter	None	±0.3 milligal author's estimate

*Accuracy tabulation based upon formulas and codes by Robbins, and others (1974) established for compilation of gravity data for California. The accuracy for the data are applicable to land-based data only. Accuracy estimates for the lake-based data come from the individual authors. Accuracy data are compiled only for those data that fall within Lakes Superior, Michigan, and Huron and those parts of Michigan that are included in the gravity map.

TABLE 3. Densities (gm/cc) of Archean and Proterozoic rocks in the Lake Superior region (modified from Oray, 1971)

Source	Jacobsville Sandstone* and Bayfield Group	Oronto Group	Portage Lake Volcanics	Pre-Keweenawan rocks
Thiel (1956)	2.30±0.06	2.36±0.12	2.90±0.10	—
White (1966a,b)	2.30	2.44	2.90	2.67
	2.37	2.62	2.92	2.70

	Archean		
Schists, slate, quartzite, metapelite, metagraywacke, and metavolcanic rocks	Granite, granite gneiss, migmatite, and pegmatite	Mafic gneiss metagabbro	
2.72±0.03	2.72 average	2.90–4.01; 3.34 average	2.50–2.80; 2.68 average	2.80–3.33; 2.92 average

*The Jacobsville Sandstone may be in part Cambrian.

SUMMARY AND CONCLUSIONS

On the basis of the factors discussed above and by correlation of gravity anomalies with geologic maps, several generalizations can be made regarding the usefulness of the gravity anomalies on the map. For example, in areas underlain by Keweenawan rocks, positive Bouguer gravity anomalies with steep gradients are caused by near surface mafic intrusive and extrusive rocks. In contrast, positive anomalies with gentle gravity gradients suggest rocks are more deeply buried, probably beneath Keweenawan sedimentary rocks, or may be caused by mafic features that occur at great depth. Negative Bouguer gravity anomalies in areas underlain by Keweenawan rocks indicate less than normal thickness of mafic lavas, or thick accumulations of Keweenawan or younger sedimentary rocks or both. In pre-Keweenawan terrane positive anomalies are usually, but not always, associated with Precambrian X basins and troughs or with mafic gneiss and greenstone belts. Negative gravity anomalies are generally located over Archean granitic terrane and over the regional metamorphic axes in northern Michigan and Wisconsin, which suggest granitic plutons at depth.

AFFILIATIONS

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